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Control of Spin Wave Dynamics in Spatially Twisted Magnetic Structures

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Abstract: The magnetization switching using spin waves is a promising method for information writing of magnetic storage devices to balance competing goals for high storage density and low power device operation. This project has capability to realize high-performance spintronic and magnetic storage devices. In order to systematically understand and effectively control the spin wave dynamics of magnetic structures twisted spatially, we prepared the exchange-coupled films with the hard magnetic $L1_0$-FePt and the soft magnetic Permalloy (Py; $Ni_{81}Fe_{19}$) layers having in an in-plane and a perpendicularly magnetized configurations. Based on the systematic investigation of the magnetic structures and the spin wave dynamics, the significant reduction of the switching field was achieved in the perpendicularly magnetized configuration (*J. Appl. Phys.* 117, 013905 (2015), *Phys. Rev. B* 94, 220401(R) (2016).). By using the in-plane configuration, on the other hand, we carefully examined the switching condition under the rf magnetic field (H_{rf}) application. As a result, we found that spin wave-assisted magnetization switching is a resonant magnetization process (*Appl. Phys. Lett.* 110, 082401 (2017).). Also, we observed the unique magnetic interaction between the nanodots of $L1_0$-FePt having perpendicular magnetization (*Appl. Phys. Lett.* 107, 152410 (2015).). These results lead to a new way for information writing of magnetic storage and spintronic applications.

Introduction and Objective:

Recent rapid progress in the research field of nano-electronics has required us to develop high-performance and multi-functional electronic devices driven with extremely low power consumption. "Spintronics", simultaneously utilizing the charge and the spin of electrons, provides us with solutions to essential problems for semiconductor-based electronic devices. In order to reduce the electric power required for the operation of spintronic devices, however, a route for highly efficient magnetization switching, which is very important to write information into magnetic bits with low external energy, is strongly desired.

We recently demonstrated the extremely low field-magnetization switching in a highly coercive FePt by using spin waves excited in a soft magnetic Permalloy (Py; $Ni_{81}Fe_{19}$), as shown in Fig. 1(a), where Py was exchange-coupled to FePt through the interface (T. Seki *et al.*, Nature Commun. 2013). We call this magnetization switching technique “spin wave-assisted switching”. We consider that spin wave-assisted switching is a key for ultrahigh density magnetic recording and large scale-integrated spintronic devices. However, the detailed mechanism of this switching has not fully been understood yet. Also, we need to examine this switching method in a perpendicularly magnetized configuration (Fig. 1(b)) in order to apply this method to practical device structures. A perpendicularly magnetized configuration has a great advantage to achieve the ultrahigh recording density.

In this research project, we aim to systematically understand and effectively control the spin wave dynamics of magnetic structures twisted spatially in an in-plane and a perpendicularly magnetized configurations. Based on the systematic investigation of their spin wave dynamics, the significant reduction of the switching field is the goal of this project. The understanding of the spin wave dynamics in nano-scaled bilayer elements is also an important aim of this project.

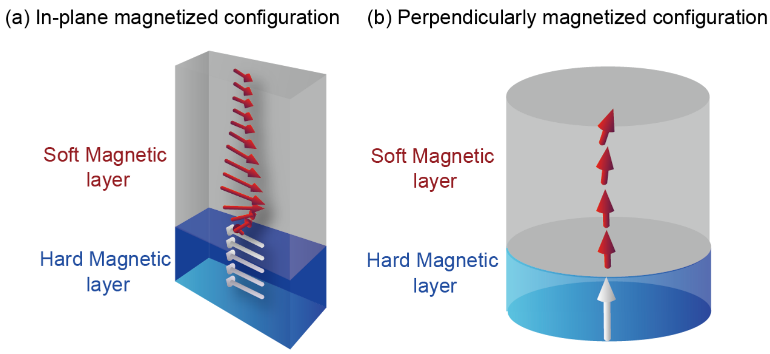

Figure 1 Schematic illustrations for exchange-coupled bilayers consisting of soft and hard magnetic layers with (a) in-plane and (b) perpendicularly magnetized configurations.

Approach/Method: The exchange-coupled films with the hard magnetic $L1_0$-FePt and the soft magnetic Py layers were prepared using sputtering technique. Using the electron beam lithography and Ar ion milling, microfabrication was carried out to prepare the well-controlled structures, which was important to obtain the magnetic structures twisted spatially in an in-plane and a perpendicularly magnetized configurations.

The structural characterization was carried out using the x-ray diffraction and Reflection high energy electron diffraction. The static magnetic properties were evaluated using the superconducting quantum interference device magnetometer, magneto-optical Kerr effect, and magnetic force microscopy (MFM). In addition, the switching fields of the microfabricated devices were evaluated by measuring the anisotropic magnetoresistance (AMR) effect of the device. Also, we applied the rf power to the device by using a signal generator, which generated H_{rf}. This AMR measurement enabled us to evaluate H_{sw} under the H_{rf} application.

Impact/Achievement: For the twisted magnetic structure in the perpendicularly magnetized configurations, we obtained the following results and achievements.

A) Perpendicularly magnetized $L1_0$-FePt nanodots exchange-coupled with soft magnetic $Ni_{81}Fe_{19}$ (*J. Appl. Phys.* 117, 013905 (2015))

The thickness dependence of magnetic properties was systematically investigated for the exchange-coupled films with the perpendicular magnetized $L1_0$-FePt and the in-plane magnetized Py layers. After patterning the $L1_0$-FePt | FeNi continuous films into the nanosized dot shapes, we have successfully formed the spatially twisted magnetic structures in the perpendicular configuration for the $L1_0$-FePt | FeNi bilayers. Figure 2 shows the full magnetization curve and the MFM images together with the schematic illustrations of the magnetic moments of a nanosized dot, where H was applied perpendicular to the film plane. These experimental results and the micromagnetic simulation suggested that the formation and the annihilation of magnetic vortex in the FeNi layer play important roles for the magnetization reversal under static magnetic field.

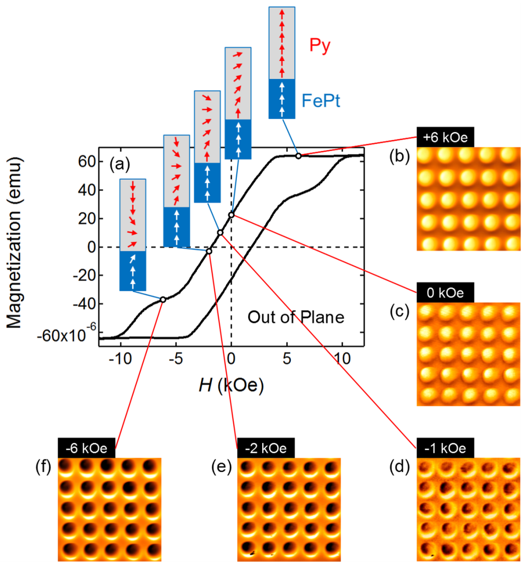

Figure 2 (a) Full magnetization curve of the nanosized dots for the MFM measurement and schematic illustrations of the magnetic moments of a nanosized dot. MFM images of the dots at (b) H = 6 kOe, (c) 0 Oe, (d) -1 kOe, (e) -2 kOe and (f) -6 kOe. H was applied perpendicularly to the film plane.

B) Vortex Dynamics-Mediated Low-Field Magnetization Switching in an Exchange-Coupled System (*Phys. Rev. B* 94, 220401(R) (2016))

We investigated the magnetization dynamics of exchange-coupled bilayers with a perpendicularly magnetized $L1_0$-FePt and a soft magnetic Py. The $L1_0$-FePt (001) layer was epitaxially grown on an MgO (100) single crystal substrate with an Au (001) buffer layer. In order to examine the effect of magnetization dynamics on magnetization switching field (H_{sw}) of the perpendicularly magnetized $L1_0$-FePt, we exploited a nanodot consisting of the $L1_0$-FePt layer and the soft magnetic Py layer having a magnetic vortex as schematically illustrated in Fig. 3(a). The $L1_0$-FePt layer exhibited H_{sw} = 8.6 kOe without the application of H_{rf}. Figure 3(b) plots H_{sw} as a function of frequency (f) of H_{rf}. Compared to H_{sw} with no H_{rf} applied, a strong reduction of H_{sw} was evident in the range of 11 GHz $\leq f \leq$ 17 GHz. When H_{rf} = 200 Oe with the frequency (f) of 11 GHz was applied, H_{sw} was reduced to 2.8 kOe. By comparing the experimental result with the micromagnetic simulation, we found that the vortex dynamics of azimuthal spin waves in Py effectively triggered the reversed-domain nucleation in $L1_0$-FePt at a low magnetic field. Our results demonstrate that the excitation of spin waves in the magnetic vortex leads to the efficient H_{sw} reduction for the exchange-coupled system having the perpendicularly magnetized $L1_0$-FePt.

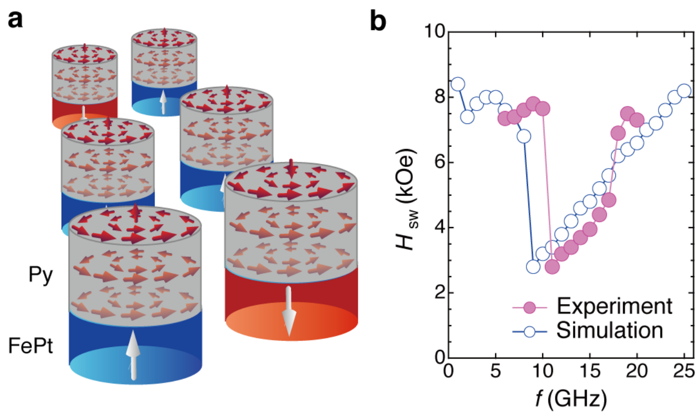

Figure 3 (a) Schematic illustration of nanodots consisting of perpendicularly magnetized $L1_0$-FePt and Py having the magnetic vortex. (b) Switching field (H_{sw}) as a function of frequency (f) of rf magnetic field.

C) Superferromagnetism in dipolarly coupled L10 FePt nanodots with perpendicular magnetization (*Appl. Phys. Lett.* 107, 152410 (2015))

The magnetic interaction between FePt nanodots was examined by measuring the magnetic properties and observing the magnetic domain structures for the FePt nanodot arrays. Consequently, we have found the unique magnetic interaction between the nanodots of $L1_0$-FePt having perpendicular magnetization, which was interpreted in the framework of the idea of superferromagnetism.

For the twisted magnetic structure in the in-plane magnetized configurations, we obtained the following results and achievements.

D) Resonant magnetization switching conditions of an exchange-coupled bilayer under spin wave excitation (*Appl. Phys. Lett.* 110, 082401 (2017))

In order to understand the detailed switching condition of spin wave-assisted magnetization switching, we mapped the switching events in the magnetic field (H) - f planes for the exchange-coupled bilayers, where $L1_0$-FePt and Py layers showed in-plane magnetization. Figure 4 The magnetization switching was observed only in a limited region following the dispersion relationship of perpendicular standing spin wave modes in the Py layer. The experimental result and the numerical simulation indicate that spin wave-assisted magnetization switching is a resonant magnetization process. This is a characteristic behavior and different from the conventional microwave assisted switching. Our results also suggest that spin wave-assisted magnetization switching has the potential to be applied to selective switching for multilevel magnetic recording media.

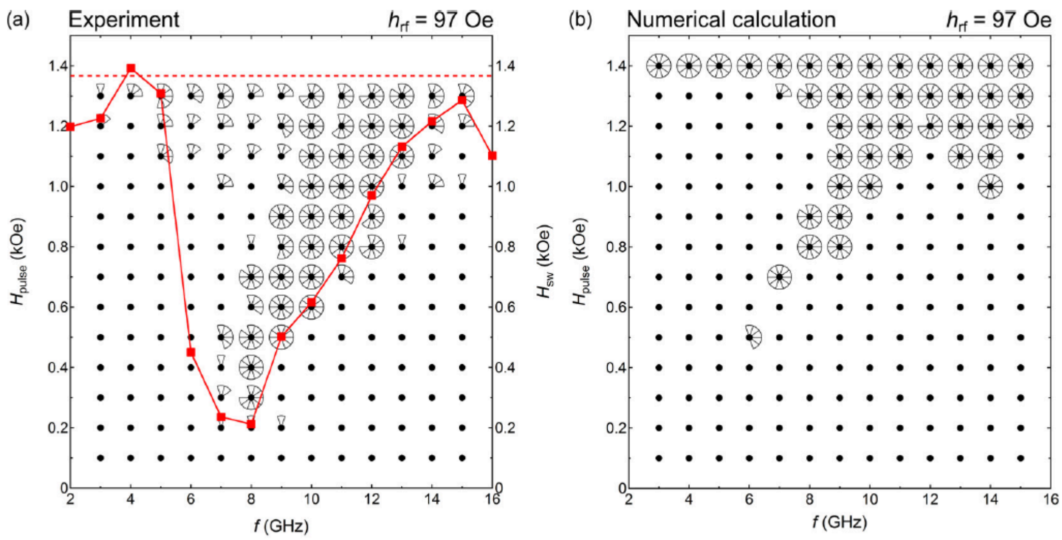

Figure 4 (a) Experimentally mapped switching events of the FePt layer in the H - f plane. The H_{rf} of 97 Oe was applied to the element. For each parameter in the plane, ten measurements were carried out, and the number of switching events is represented by the number of sectors. Red squares plot the average H_{sw} measured under continuous H_{rf} application with the same rf power input. The red dashed line indicates H_{sw} without H_{rf} application. (b) Switching conditions obtained from the numerical calculation. H_{rf} was fixed at 97 Oe.

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Date: 5 January 2015

Journal name: *Appl. Phys. Lett.* 107, 152410-1-4 (2015).
Title: Superferromagnetism in dipolarly coupled $L1_0$ FePt nanodots with perpendicular magnetization
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